Technical Note 1971-51

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Vibration and Strain-Induced Noise from the ELF Flexible Loop Antenna

15 December 1971

Prepared for the Department of the Navy
under Electronic Systems Division Contract F19628-70-C-0230 by

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Lexington, Massachusetts

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LINCOLN LABORATORY

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Consultant to Group 66

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The work reported in this document was performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology. The work was sponsored by the Department of the Navy under Air Force Contract F19628-70-C-0230.

ABSTRACT

Measurements have been made on a segment of the ELF flexible loop antenna to study its electrical sensitivity to vibration and strain. Transfer functions for the output voltage resulting from various types of vibration and strain were determined as functions of frequency, bias current, and orientation with respect to the gravitational field. Based on these laboratory measurements, it is tentatively concluded that the principle source of noise for the flexible loop antenna towed from a submarine is longitudinal strain.

Accepted for the Air Force
Joseph R. Waterman, Lt. Col., USAF
Chief, Lincoln Laboratory Project Office

VIBRATION AND STRAIN-INDUCED NOISE FROM THE ELF FLEXIBLE LOOP ANTENNA

A series of laboratory experiments have been conducted on a two foot segment of the ELF flexible loop antenna containing one 30-wire bundle core segment.[1] The purpose of these experiments was to determine the voltage generated by the antenna when it is subjected to different types of vibration and strain. The dependence of the voltage-output level on frequency, bias current, level of vibration or strain, and orientation of the antenna segment with respect to the earth's gravitational field was determined.

1. Summary of Results

The most significant result of the laboratory experiments was the determination of vibration to voltage output transfer functions for the different types of vibration and strain applied to the segment. Five types of vibration were used in the experiments. These are shown in schematic form in Fig. 1 and listed below:

Vibration Type	Description
I	Pitching in the vertical plane about the center point of the segment
II	Translation of the segment vertically
III	Translation of the segment longitudinally
IV	Bending of the segment in the vertical plane with clamped end points
V	Stretching of the segment longitudinally with one end clamped.

In each experiment the excitation and supports of the segment were arranged so that one type of vibration was dominant in determining the voltage-output. The vibration generator - an electromagnetic shaker, located six feet from the segment to avoid pickup of the shaker magnetic field by the antenna - was excited by a swept pure tone with frequency varying from 0 to 200 Hz. The resulting voltage was measured in a 3 Hz band with center frequencies

1. M. L. Burrows, et al., "Fabrication of Flexible Loop Antenna," TN 1970-31, Lincoln Laboratory, M.I.T. (5 October 1970), DDC AD 717718.

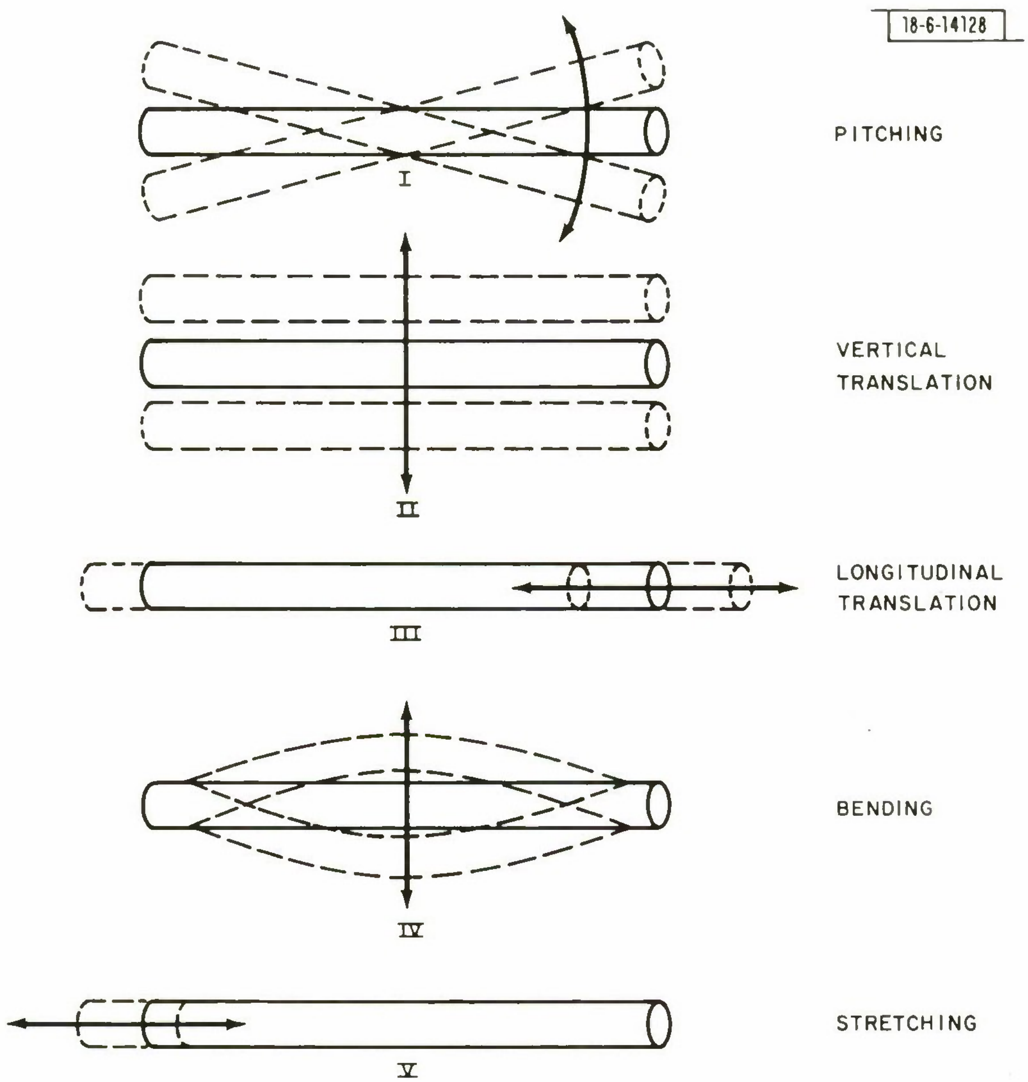

Fig. 1. Types of vibration used for the flexible loop antenna laboratory tests - motion exaggerated for illustration.

equal to the frequency of excitation.

Transfer functions for the voltage-output resulting from the different types of vibration are plotted in Fig. 2. These functions are valid for a large range of vibration levels. However, nonlinearity was observed at high excitation levels for Type IV (bending) and Type V (stretching) vibration (Fig. 14). Voltage generated by Types II, III, IV and V vibration was determined to be magnetostrictive since a large decrease in the noise occurred near +2.0 ma bias current (Fig. 12).

It is impossible to determine which types of vibration are responsible for the noise generated in the sea tests, since vibration measurements on the towed cable are not presently available. However, a significant amount of evidence indicates that electrical noise measured in the sea trials is a result of longitudinal stretching of the cable.

2. Experiment Set-up

One goal of the laboratory experiments was to determine quantitatively the amount of vibration induced noise generated by the antenna for different types of vibration. At the onset of the experiments, it was expected that the noise due to the different types of vibration would be different in both level and character. Thus, an experimental setup was designed which allowed precise control of the type of vibration and its level. This set-up is shown in Fig. 3.

Three of the different types of vibration shown in Fig. 1 are rigid body motions of the antenna segment. To eliminate the possibility of bending or stretching of the antenna segment during these rigid body motions it was enclosed in a very stiff light-weight beam; a cross-section of the beam is shown in Fig. 4. The materials used are non-metallic so that the performance of the antenna is unaffected. The antenna segment was carefully located at the center of the beam and bonded in place with a rigid epoxy. The glass face sheets were also bonded to the balsa wood core using a rigid epoxy. By use of this design very high bending and torsional stiffness are

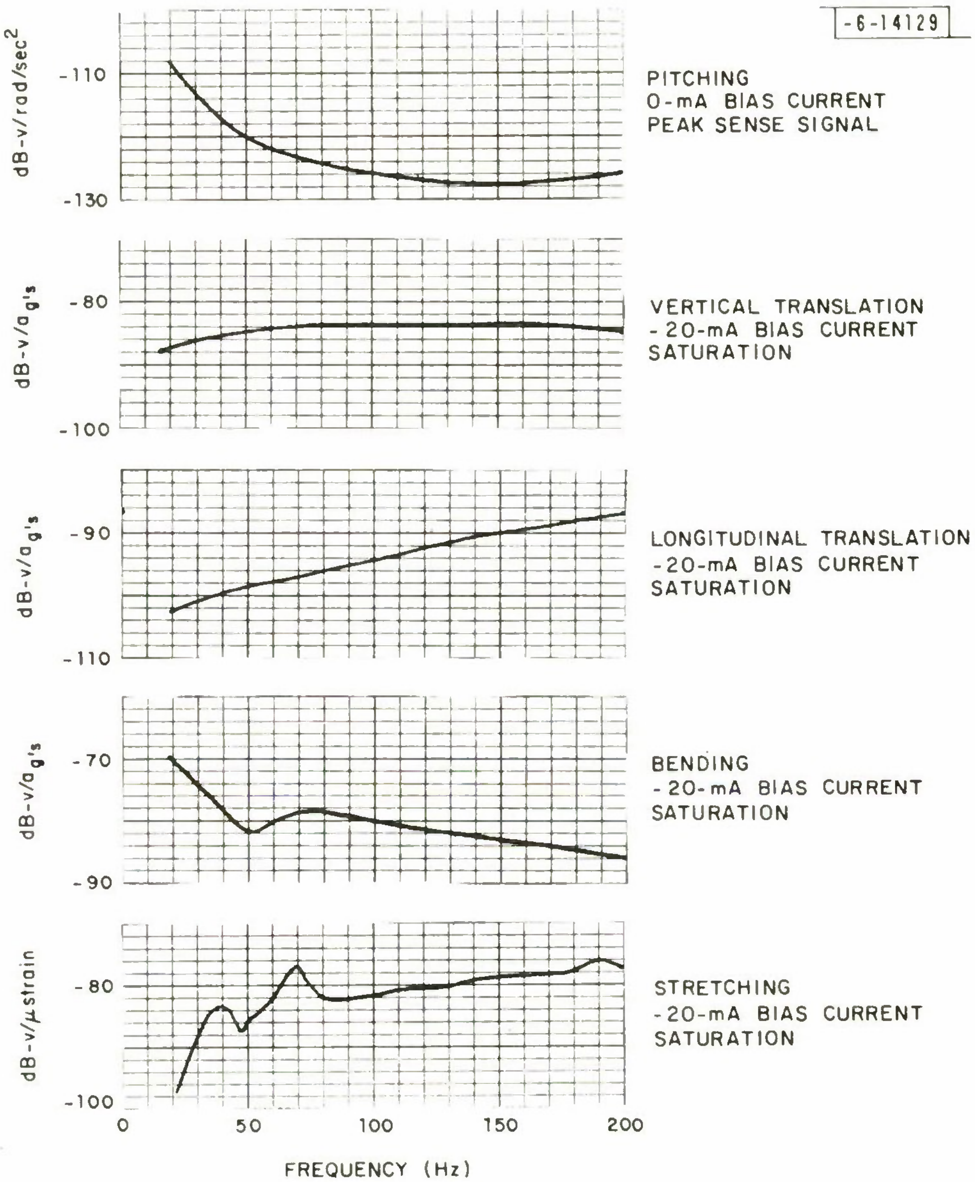

Fig. 2. Transfer functions relating antenna segment output voltage to vibration level for different types of vibration.

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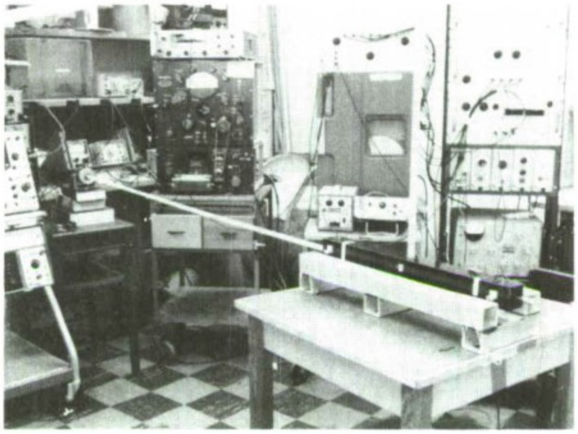
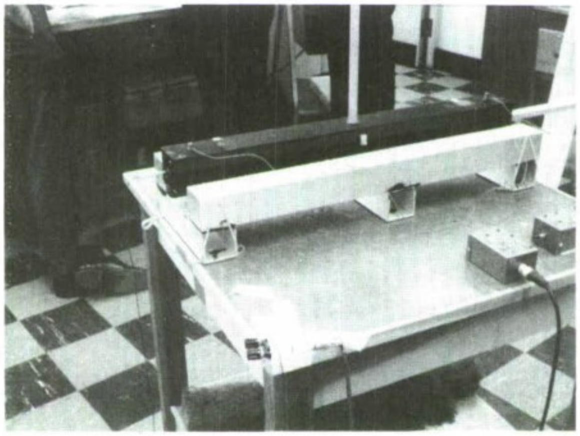


SET-UP FOR COMBINED VERTICAL
AND LONGITUDINAL EXCITATION



BEAM ENCLOSING ANTENNA SEGMENT
FOR RIGID BODY VIBRATION TEST

Fig. 3. Experimental set-up.

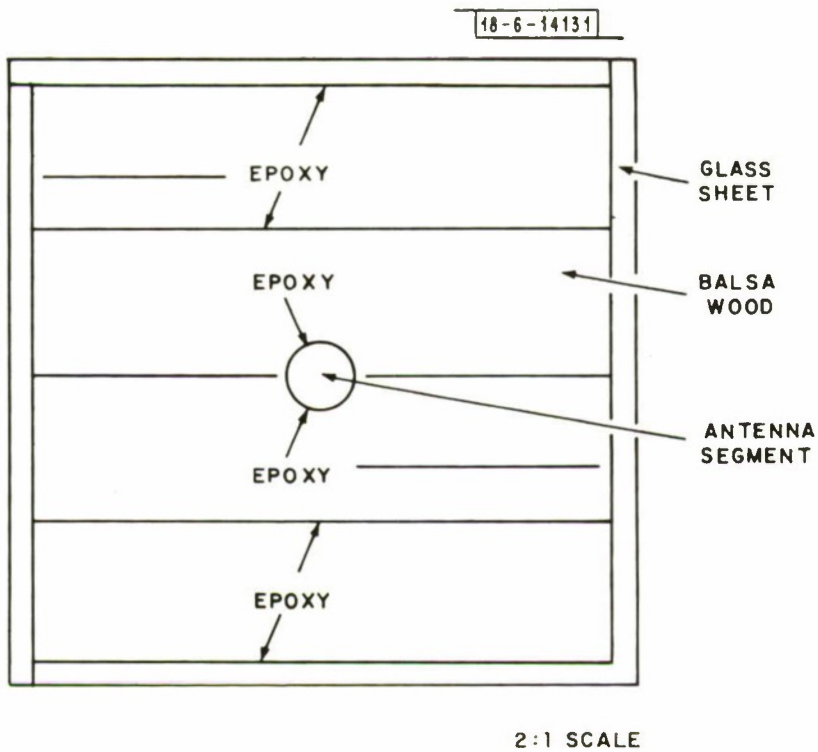


Fig. 4. Cross-section of beam enclosing antenna segment.

obtained with a very light-weight design. The dimensions of the beam were selected so that the first bending and torsional resonance frequencies of a 2 foot long beam with free boundary conditions would be above 500 Hz. Measurements of the first bending resonance frequency set it at 620 Hz. Since the bending and torsional resonance frequencies are well above the frequency range of interest for the experiments, 0 - 200 Hz, the beam can be considered to be rigid.

Two small 3 lb. force electro-magnetic shakers were used to excite the beam and antenna segment. To prevent the magnetic field of the shakers from interfering with the performance of the antenna, the shakers were located 5 feet above the antenna and connected to the antenna beam by 1/2 in. by 1/2 in. balsa wood beams. Measurements of the pickup of the shaker field by the antenna were made during the experiments and indicated that the signal resulting from this pickup was less than the vibration-induced signal for all types of vibration.

An aluminum test fixture was designed to support the antenna beam during the experiments. This fixture and the general experiment setup is shown in Fig. 3. The fixture was designed so that it has no resonances in or near the frequency range 0 to 200 Hz.

A number of different methods of supporting the antenna beam on the test fixture were tried. The most satisfactory method was to stretch two rubber bands from rail to rail at each end of the test fixture. The antenna beam was placed on top of these rubber bands between the two fixture rails. The fixture in turn was supported on the top of a small wooden table which was isolated from the floor vibrations by foam rubber pads. Measured vibration of the antenna beam without applied excitation from the shakers is shown in Fig. 5. Except near 30 Hz the vibration levels are below the noise floor of the accelerometer.

To establish the noise floor of the antenna-receiver system two measurements were made. First, the receiver input was shorted and the

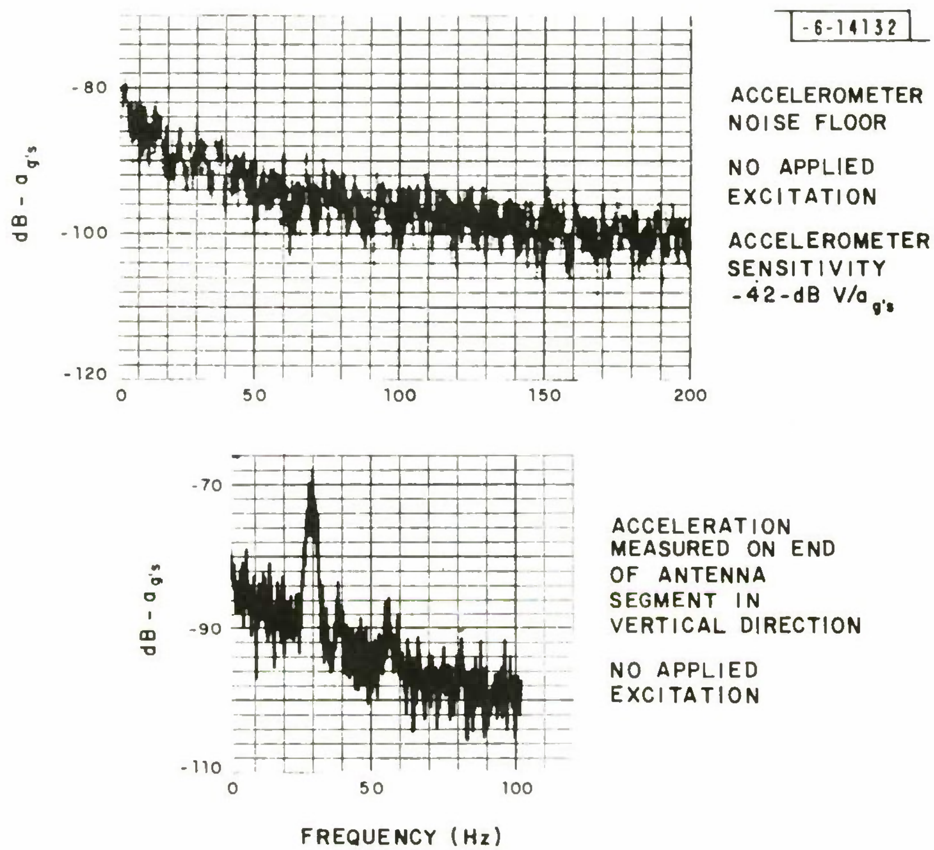


Fig. 5. Antenna segment vibration levels with no applied excitation.

output noise spectrum in 3 Hz bands was plotted, as shown in Fig. 6. Peaks at 60, 120 and 180 Hz are due to pickup of the line frequency. Gain of the receiver (Loop Receiver - 3) is expressed as the sum of three numbers - a fixed 20 dB gain to cover the additional gain of the receiver preamplifier due to a new matching transformer (G309) for use with the 2 foot antenna segment, the standard receiver preamp gain either 40 or 60 dB and the amplifier gain 0 to 50 dB in 10 dB steps.

Figure 7 shows the antenna segment output noise when there was no applied excitation from the shakers. Peaks at 60, 120 and 180 Hz result from pickup of the 60 Hz field in the laboratory. We suspect that the noise floor shown in Fig. 7 is vibration-induced even though the levels of vibration could not be measured using our accelerometers. In any case the levels shown in Fig. 7 are well below those measured during the remaining experiments.

Instrumentation for the experiments was straight-forward. The output signal of a General Radio Model 1900-A Wave Analyzer was set to be 0.1 vrms, attenuated by a variable attenuator, amplified by a fixed gain 20 dB amplifier, split and amplified by two variable gain AC amplifiers and the two signals used as inputs to the shakers. The variable gain amplifiers were adjusted to equalize the force generated by each shaker. The accelerometer outputs were used as inputs to a sum and difference amplifier. The sum signal or the difference signal, as desired, was amplified and recorded on the GR 1521-B Level Recorder. The antenna output was amplified using Loop Receiver-3 and recorded on the GR Level Recorder. Degaussing Unit-1 was used to provide both fixed and swept bias currents over the range -20 ma to +20 ma. Vibration and antenna signal recordings were made sequentially. Changes in the vibration levels during each experiment did not occur. For all recordings the analysis bandwidth of the GR analyzer was set at 3 Hz, the chart speed at 1.5 in/sec., and the pen writing speed at 3 in/sec. All measurements were made with pure tone excitation.

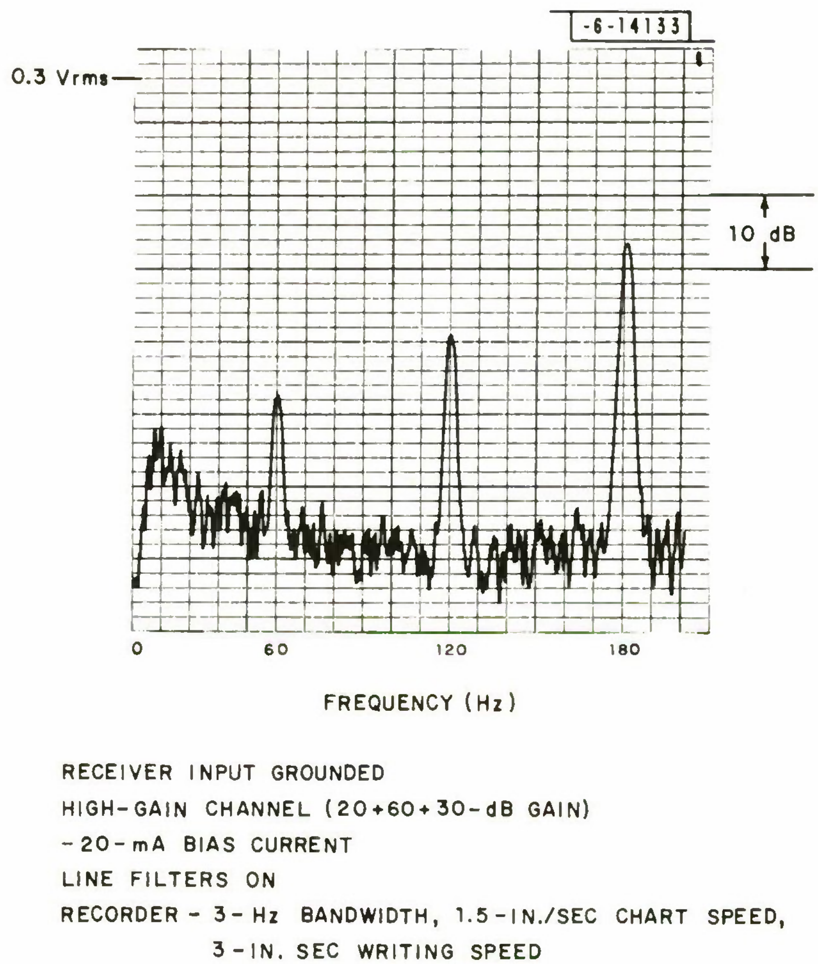
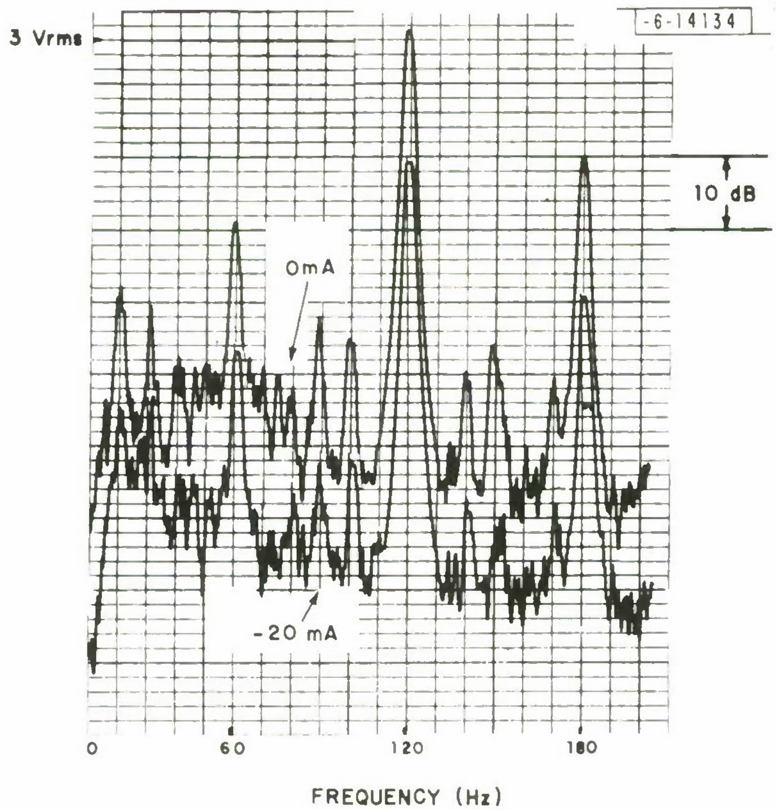


Fig. 6. Noise floor with receiver input grounded.



HIGH-GAIN CHANNEL, 20+60+30-dB GAIN
LINE FILTERS ON
VIBRATION AS SHOWN IN FIG. 3
-20 AND 0-mA BIAS CURRENT
RECORDER - 3-Hz BANDWIDTH, 1.5-IN./SEC CHART SPEED,
3-IN./SEC WRITING SPEED

Fig. 7. Antenna segment noise with no applied vibration.

3. Vibration - Induced Noise as a Function of Frequency

Noise measurements have been made during a sea test for the 50 and 150 foot antenna . The high levels of noise found in these tests remain largely unexplained. In an effort to explain the causes of this noise, sea trials are planned in which a cable instrumented with strain gages will be used to gather basic vibration data for towed cables. This data can be used with the laboratory measurements described herein to predict the noise of the 50 and 150 ft. flexible loop antennas and to identify the type of vibration which is the dominant source of noise in the sea tests.

Using the setup described in the previous section transfer functions have been determined for each of the types of vibration shown in Fig. 1. These transfer functions, which are shown in Fig. 2, allow one to convert a random vibration spectrum to an electrical noise spectrum for the antenna as long as the different types of vibration are uncorrelated. If the different types of vibration are correlated it is necessary to know the phase relation between input vibration and electrical signal in addition to the transfer functions shown in Fig. 2.

Some data on the antenna output under combined motions were taken during the experiment. However, the amount of data is not sufficient to establish the relative phase relation between vibration input and electrical signal output.

To find the transfer function for pitching and vertical translation, two shakers were used to excite the antenna beam - one connected to each end of the beam. The shakers were suspended from the ceiling by means of rubber bands so that the ceiling vibrations would not be transmitted to the shakers and to the antenna beam. By exciting the shakers 180° out of phase a vibration was generated which was predominantly vertical pitching as shown in Fig. 1. By exciting the shakers in phase a vibration was generated which was predominantly vertical translation.

At low frequencies, near 20 Hz, a resonance in both the pitching and translation vibration occurred as shown in Fig. 8. This resonance was a rigid body resonance of the antenna beam on the rubber band supports. In addition, the difference between pitching and translation at low frequencies, below 30 Hz, is less because the low frequency characteristics of the two shakers was quite different. Use of identical shakers would maintain the difference between pitching and translation at all frequencies.

The vibration of the antenna beam was measured using two small, 2 gm, accelerometers - one placed at each end of the beam near the shaker attachment point. Since the beam is rigid over the frequency range of interest, measurement of the acceleration at each end of the beam can be used to specify the beam motion. The sum of the accelerations indicates the translation while the difference indicates the pitching.

The sensitivity of each accelerometer is 8 mv/g. Calibration checks were carried out many times during the experiments to verify this sensitivity.

Measurements of horizontal pitching and translation were also made during the experiments. These measurements showed the horizontal vibration to be less than either vertical pitching or translation.

Measurements of roll of the antenna beam about its center line showed this type of motion to be negligibly small.

The applied vibration levels and measured antenna output for the vertical pitching experiment are shown in Fig. 8. The measured sum and difference acceleration signals have been converted to the acceleration level in dB ref. 1 g rms at a point 11" from the center of the antenna beam. The measured electrical output of the antenna during the pitching experiment is also plotted in Fig. 8. This measured output can be compared with the predicted output due to the measured vertical translation.

The bias current for the pitching experiment was set a 0 ma. This value of bias current was very near the point of peak sense signal for the

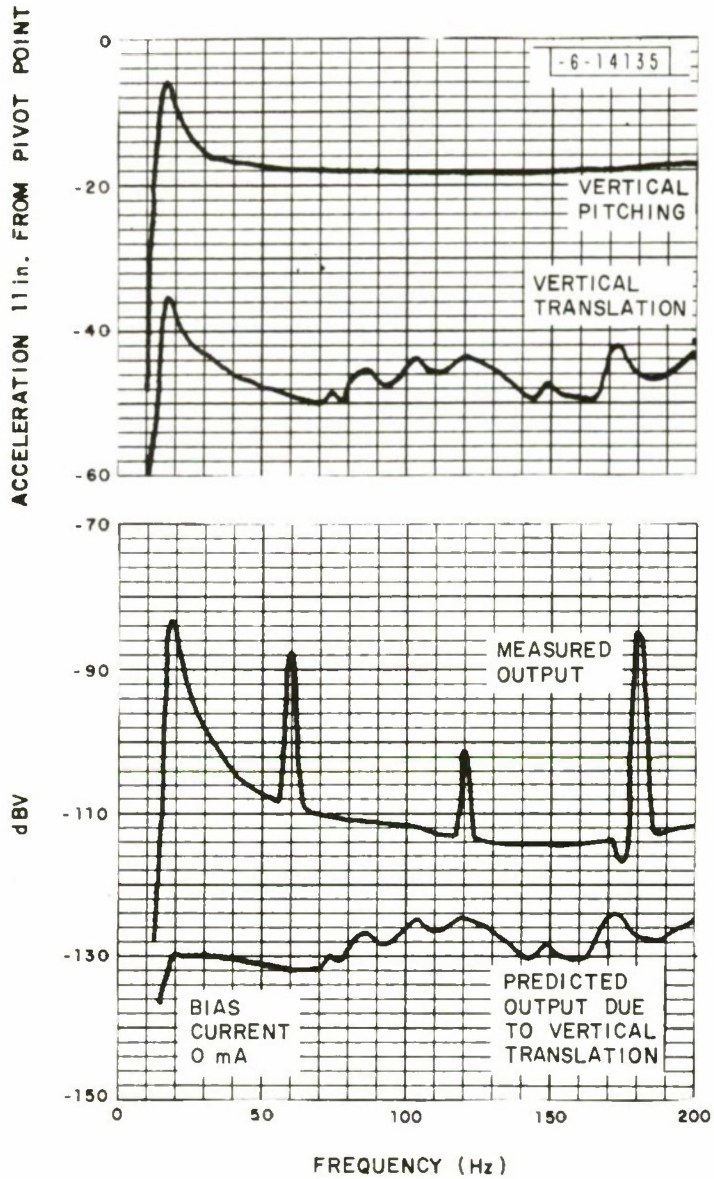


Fig. 8. Antenna segment output due to vertical pitching.

particular antenna orientation used in the experiments.

The predicted output shown in Fig. 8 was obtained using measured data at 0 ma bias current from the vertical translation experiment. Antenna output due to all other motions was predicted to be below the output due to vertical translation.

The peaks in the measured output at 60, 120 and 180 Hz were not due to vibration but to pickup of the 60 Hz field in the laboratory.

The applied vibration levels and measured antenna output for the vertical translation experiment are shown in Fig. 9. The measured sum and difference acceleration signals have been converted to the acceleration level in dB ref. 1 g rms at a point 11 " from the center of the antenna beam.

The measured output shown in Fig. 9 can be compared with the predicted output due to pitching motion except at the lowest frequencies the output due to pitching does not contribute to the measured output signal.

The bias current for the plots shown in Fig. 9 was -20 ma, so that the core was saturated. As will be seen in section 4 the output due to vertical translation is magnetostrictive and shows a null near +2 ma bias current.

The setup required to generate longitudinal rigid body motion, type III as shown in Fig. 1, was somewhat different than that described above. The shakers were removed from the ceiling and one shaker was placed in line with the antenna beam center line. As before the connection between the shaker and the beam was made using a 1/2 in. by 1/2 in. balsa beam so that the shaker was 5 feet from the antenna. Measurements showed that the antenna signal due to pickup of the shaker magnetic field was less than that due to the longitudinal motion.

Measurements of the longitudinal motion, shown in Fig. 10, were made by placing the accelerometers on one end of the antenna beam so that the sum signal would indicate the longitudinal acceleration. Measurements of

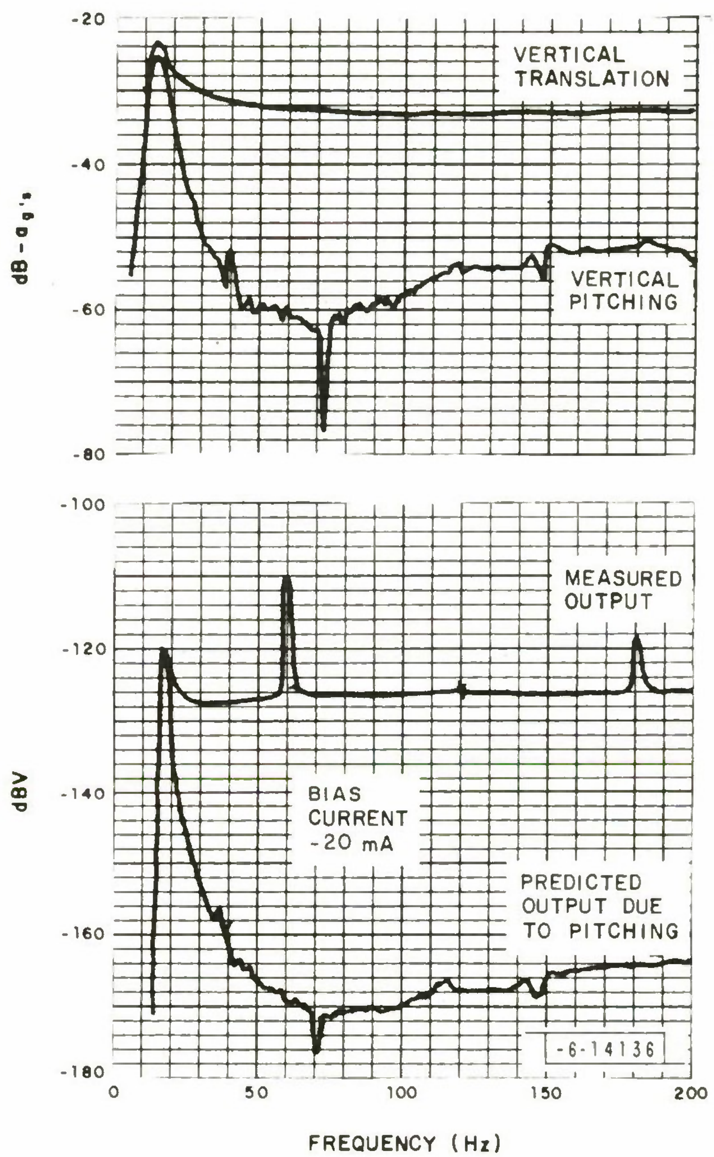


Fig. 9. Antenna segment output due to vertical translation.

the vertical and horizontal pitching and translation were also made. These measurements showed that the antenna output due to these other motions was at least 10 dB below the measured output. The predicted output due to vertical translation is also shown in Fig. 10.

The bias current for the plots shown in Fig. 10 was -20 ma. As for the case of the vertical translation the output due to longitudinal translation was magnetostrictive, although vibration-induced output due to the observed null was not very deep.

Measurement of the vibration-induced output - due to bending and stretching of the antenna segment required that the beam enclosing the segment be cut down so as to be more flexible. The glass face sheets were removed and the balsa wood core was cut down to be 1/2 in. square. The aluminum test fixture was turned over so that the three cross members connecting the rails were on top. One quarter inch aluminum blocks were placed on the end cross members and the antenna beam was placed with one end on each of these blocks.

For the bending experiment the ends of the antenna beam were clamped to the test fixture. One shaker was located over the center of the beam and connected to it by a 4 - 1/2 ft. 1/2 in. by 1/2 in. balsa beam. Acceleration measurements were taken at the center point of the beam, at each end of the beam, and at a point 1/4 of the beam length from one end. Both vertical and horizontal accelerations were measured. The predominant motion was found to be bending in the vertical plane with a spatial distribution corresponding to the first mode shape of the clamped beam. Measurements of this motion are shown in Fig. 11. The measured antenna output is also shown in Fig. 11. As for the previous two cases the output was magnetostrictive.

For the stretching experiment only one end of the antenna beam was clamped to the aluminum fixture. The other end was connected to a shaker in line with the center-line of the antenna beam by means of the 4 - 1/2 ft. balsa wood beam. Tabs were glued to the end of the antenna beam so that a

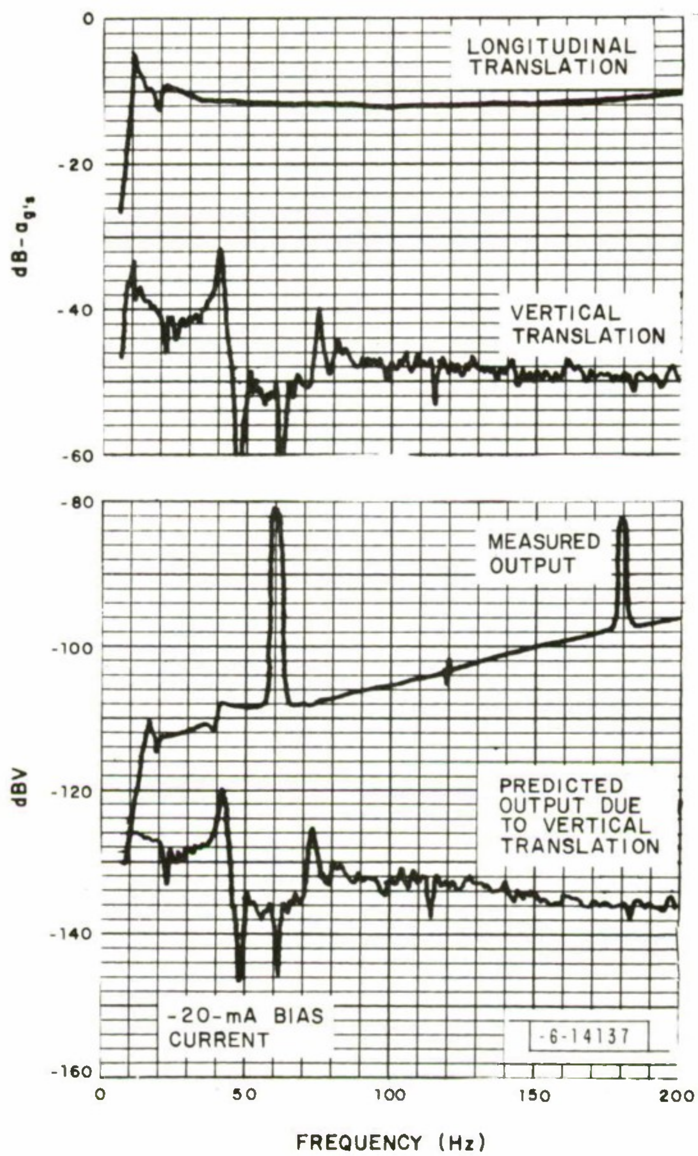


Fig. 10. Antenna segment output due to longitudinal translation.

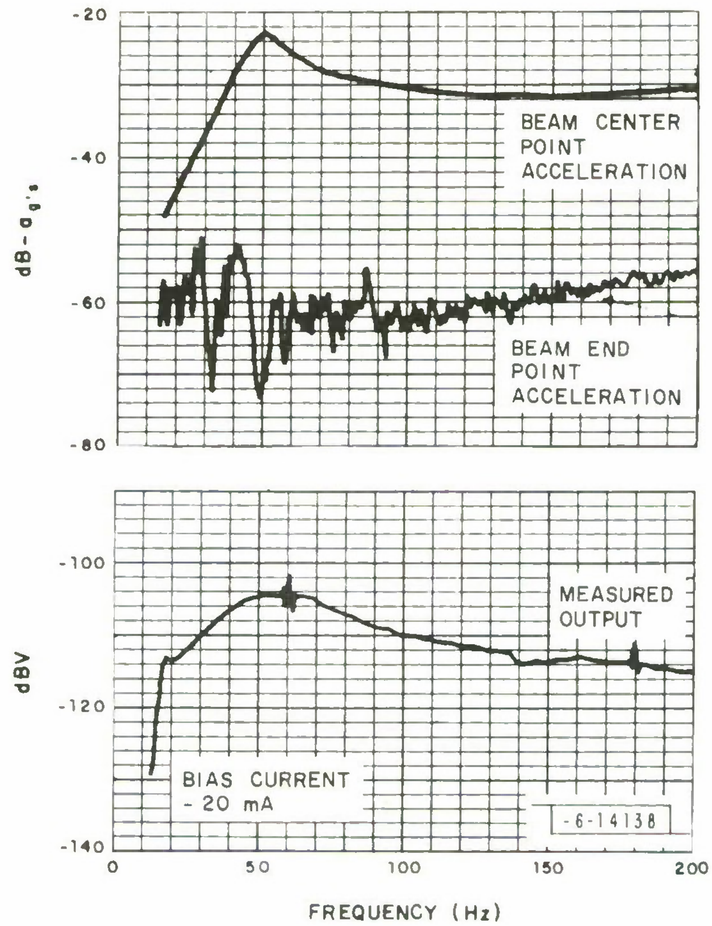


Fig. 11. Antenna segment output due to bending.

measurement of the longitudinal acceleration could be made. Measurements of the longitudinal acceleration at the clamped end of the beam were made and found to be negligible. Horizontal and vertical measurements of the transverse acceleration were also made.

In both the bending and stretching experiments the antenna output signal due to other types of vibration was at least 10 dB below the measured signal. Also the signal due to pickup of the shaker magnetic field was negligible compared to the measured signal.

The acceleration level measured in the stretching experiment showed large variations in frequency due to excitation of the bending modes of the 1/2 in. by 1/2 in. balsa beam. Therefore, a transfer function was established by adjusting the input at each frequency so that the end point acceleration level equalled -63 dB ref. 1 g rms. The resulting output at each frequency was then measured at zero bias current. Measurements were taken every 10 Hz from 20 to 200 Hz.

A transfer function for -20 ma bias current was established using bias current sweep data. This data showed the output at 0 ma to be 7 dB above the output at -20 ma for a frequency of 45 Hz. We have used this 7 dB correction at all frequencies to establish a transfer function for -20 ma. This procedure is by no means exact. However, since the magnetostrictive null is at 2 ma, it seems reasonable that the increased output at 0 ma, 45 Hz is due to increased antenna sensitivity and, therefore, the 7 dB correction can be used at all frequencies.

4. Vibration - Induced Noise as a Function of Bias Current

An important variable governing the vibration-induced noise is the bias current. By slowly sweeping through the bias current a point is reached at which the standing flux in the core is zero. At this point any vibration-induced magnetostrictive electrical output will disappear. As shown in Fig. 12 all types of vibration except pitching exhibit a null as a function of bias current. Presence of this null indicates that the outputs

due to these motions are magnetostrictive.

The null for each type of motion should occur at the same bias current. As shown in Fig. 12, however, this is not the case. The author has no satisfactory explanation for this fact. Orientation of the antenna segment with respect to the earth's magnetic field was carefully kept the same for all experiments. The small changes in orientation which could have occurred were not large enough to cause the variations in the nulling bias current shown in Fig. 12.

The depths of the magnetostrictive nulls shown in Fig. 12 are also quite varied. In the case of vertical translation, the output level in the null was calculated to be due to the pitching motion. This is also probably the case for stretching. However, the level of the output due to pitching does not explain the shallowness of the nulls for longitudinal translation and bending. No satisfactory explanation for these nulls has been found.

Magnetostrictive nulls during the sea trials with the 50 ft. and 150 ft. flexible loop antennas occurred at bias currents that were frequency dependent. In the laboratory experiments with the 2 ft. antenna segment, this same effect was found. However, the total shift of the null location was less than 1/4 ma for vertical translation, longitudinal translation and bending. Bias current sweeps at different frequencies for stretching motion were not obtained.

In investigating the output due to vertical translation, bias current sweeps were made for different orientations of the bifurcated tube. The results and the orientations are shown in Fig. 13. These results show that the orientation of the tube has a large effect on the location of the null and its depth. The orientation of the bifurcated tube was found not to have an effect on the location of the null for other types of vibration.

A possible noise mechanism is that a mechanical input couples into the sensitivity of the loop antenna and modulates the field produced by the fixed bias current. To test whether or not this mechanism was indeed

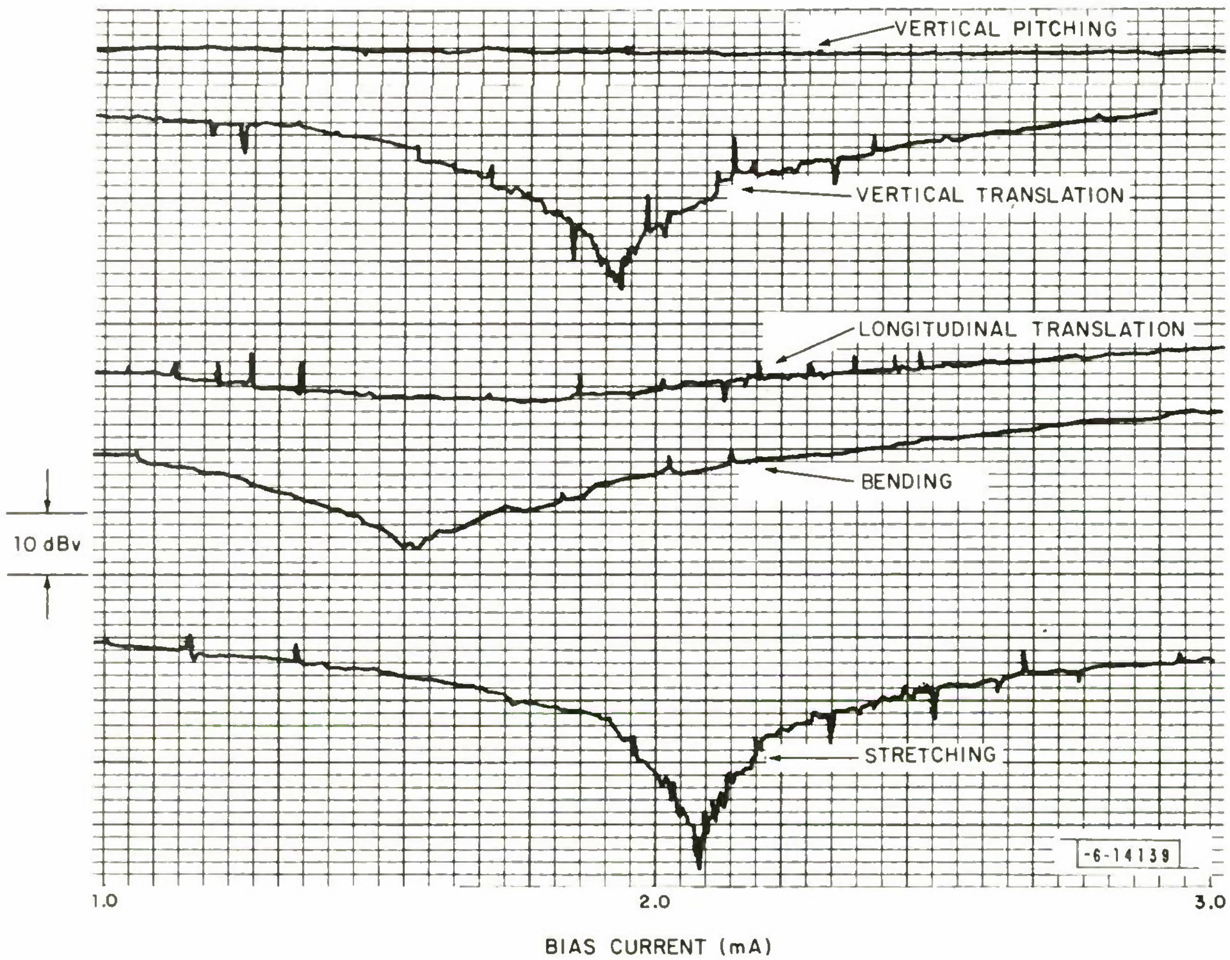


Fig. 12. Antenna segment output as a function of bias current for different types of vibration, 45 Hz.

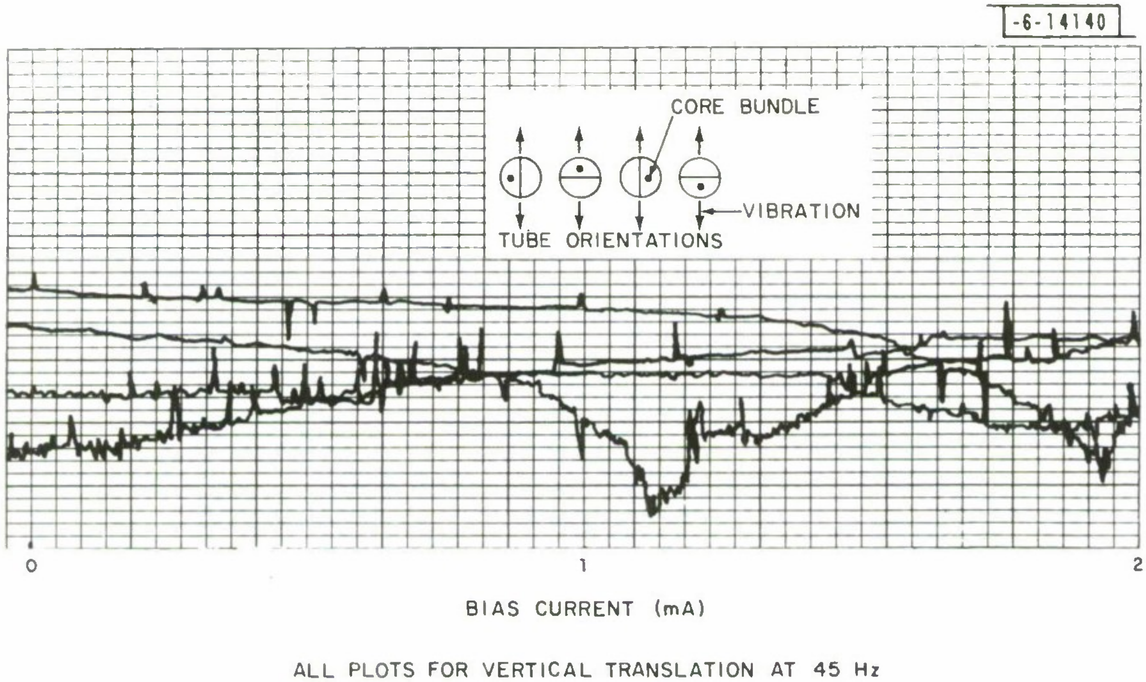


Fig. 13. Antenna segment output as a function of bias current for different orientations of the bifurcated tube.

present in the antenna segment, the segment was rotated 90° with respect to the earth's magnetic field. Sweeping the bias current the null moved from near 2 ma to near 6 ma, but the overall noise level did not change. This indicated the noise mechanism was not present, since noise generated in this manner would be dependent on the level of the bias current.

5. Linearity of the Vibration-Induced Output

The range of linearity between the antenna output and the applied vibration was established at 45 Hz. for all types of vibration. Results are shown in Fig. 14. The outputs due to pitching, vertical translation, and longitudinal translation were found to be linear over a broad range of vibration levels. The outputs due to bending and stretching showed pronounced nonlinearity.

A possible explanation for this nonlinearity is that at low levels the core bundles, which rest against the bifurcated tube, stick to the tube through static friction. The longitudinal stress in the tube is transmitted directly to the core. At higher vibration levels, the bundles slip on the tube so that the amount of stress transmitted from the tube to the core bundle epoxied into the tube, support this conclusion. These experiments will be described in section 6.

To investigate further the nonlinearity during bending and stretching vibration, the antenna segment was excited at a single frequency and the output was analyzed to determine the distortion. Results for bending are shown in Fig. 15 for a 45 Hz fundamental frequency of excitation. Those for stretching are shown in Fig. 16 using a 25 Hz fundamental frequency. In both cases the levels of the higher harmonics of the fundamental excitation frequency are quite large.

6. Experiments with the Core Bundle Epoxied into the Bifurcated Tube

All of the experiments described in previous sections were conducted with an antenna segment in which one core bundle was immersed in Freon in the bifurcated tube. In the initial design of the antenna cross-section it

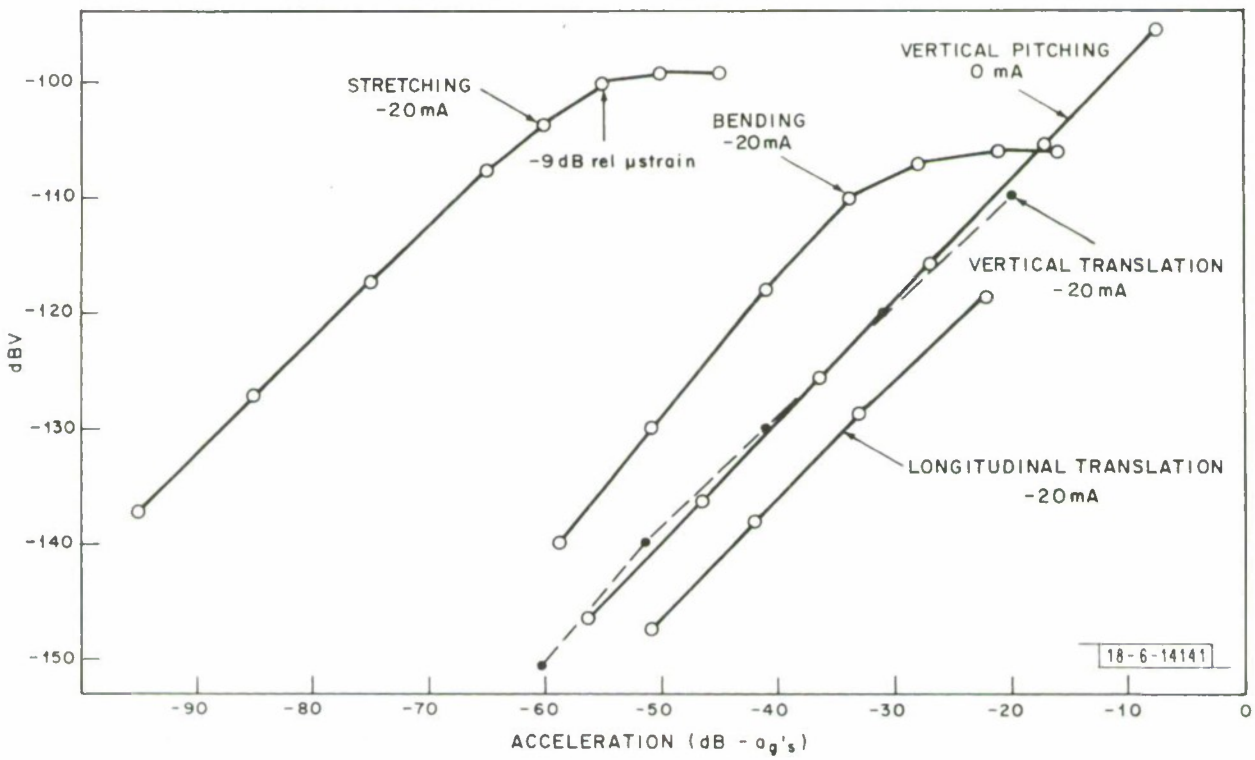


Fig. 14. Linearity of the antenna segment output for different types of vibration, 45 Hz.

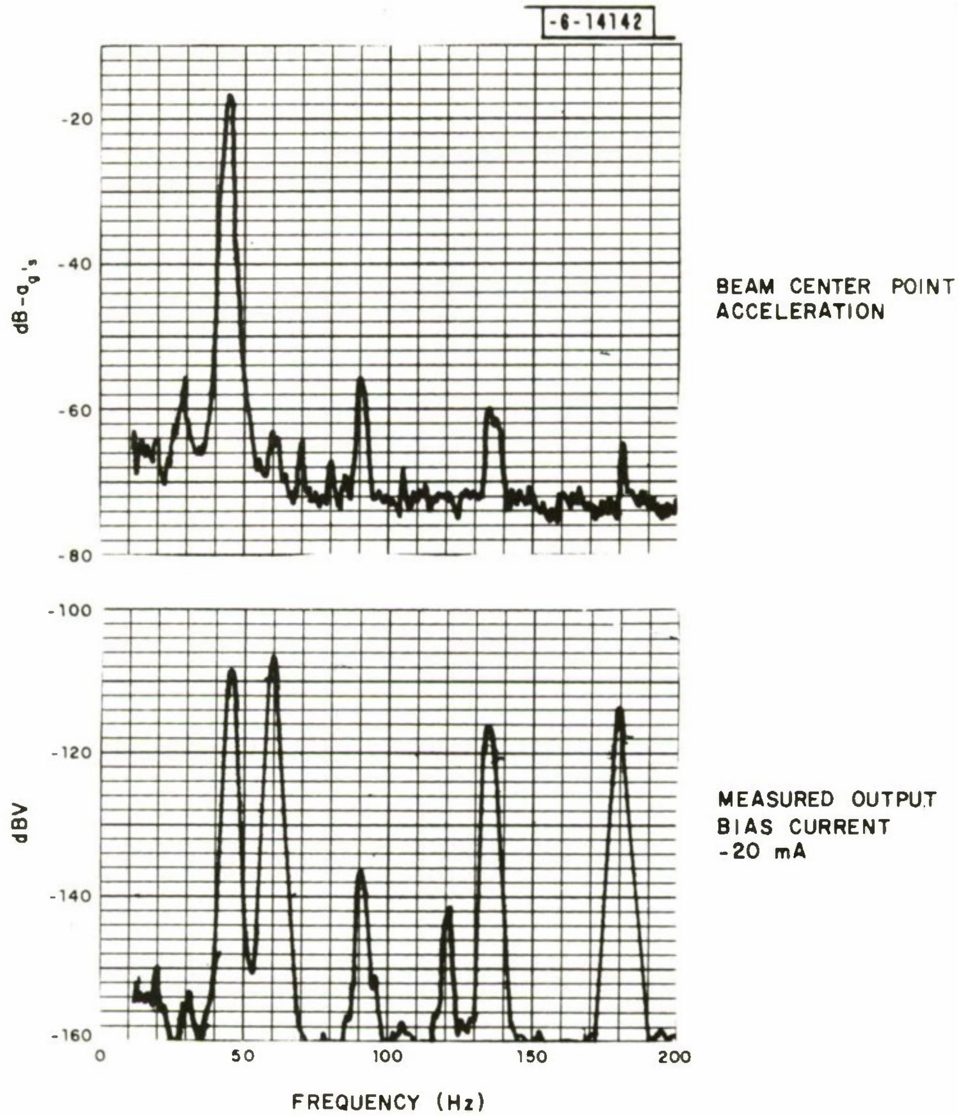


Fig. 15. Frequency distortion due to nonlinearity, bending vibration.

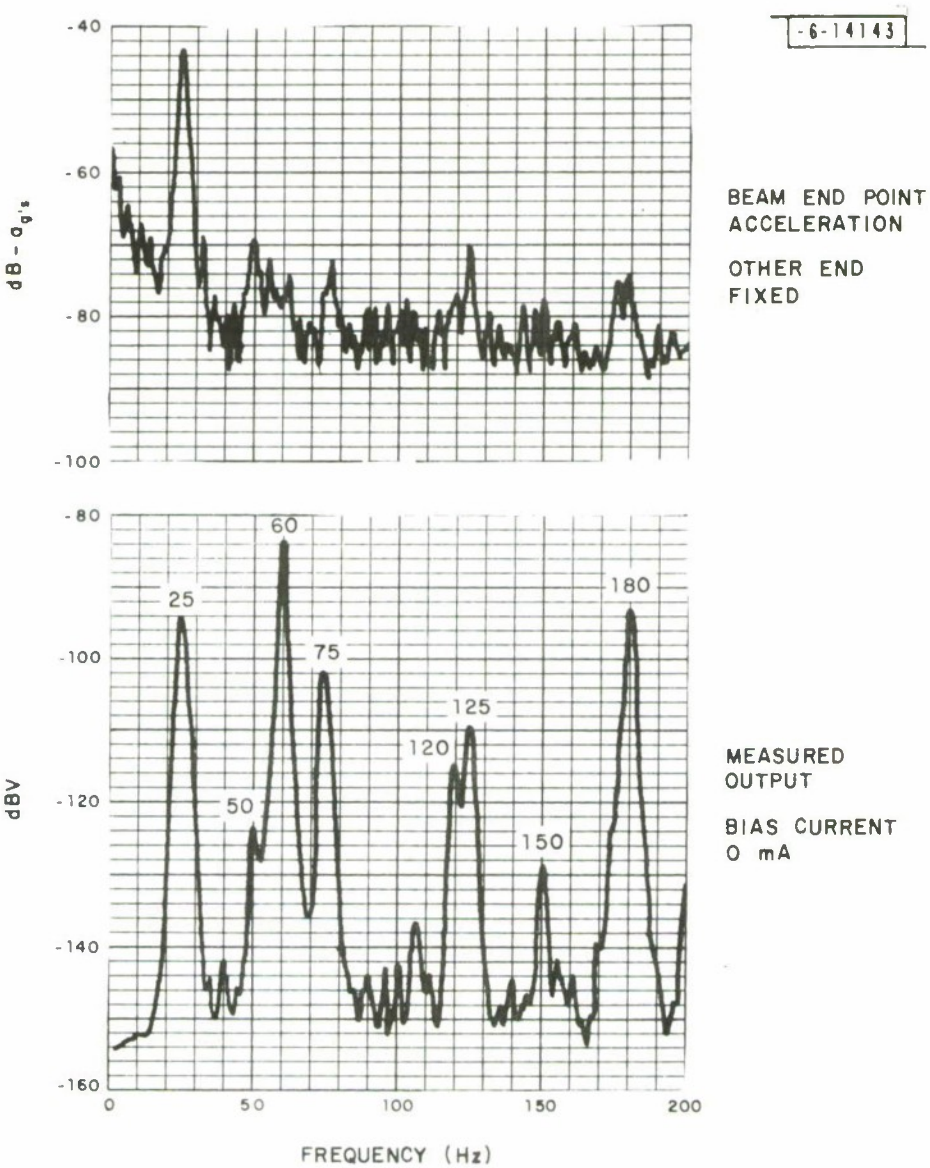


Fig. 16. Frequency distortion due to nonlinearity, stretching vibration.

was hoped that the Freon would isolate the core from any strain in the tube, coil and cable, thereby decreasing the magnetostrictive noise due to stretching of the antenna.

Data taken in our experiments indicated that there was still a significant amount of magnetostrictive noise due to stretching. To complete our experiment the core bundle and Freon were removed from the tube, the tube was filled with epoxy, and the core bundle was put back in the tube. Thus, after the epoxy hardened the core was bonded along its entire length to the tube.

Three vibration experiments were conducted with the core epoxied. First the 1/2 " by 1/2" cut-down balsa-antenna segment was fastened to a 4" by 4" glass-balsa beam using two-sided adhesive tape. The glass-balsa beam was then excited into predominantly vertical pitching, the acceleration on the antenna segment was measured, and the antenna output was measured. Results are shown in Fig. 17.

The antenna output during the pitching vibration was found to be 14 to 26 dB below the output measured previously. At low frequencies the drop in level resulted from decreased sensitivity of the core. Somehow, during the epoxying of the core, it was subjected to too much strain and lost sensitivity. Comparison of the antenna segment's inductance before and after epoxying showed approximately a 3:1 decrease. At high frequencies the drop in the antenna output due to pitching was due, in part, to loss of sensitivity and in part to elimination of some magnetostrictive noise previously observed at 200 Hz.

Experiments were also conducted with the antenna subjected to vertical translation. Results are shown in Fig. 17. These results are of questionable validity. Since the antenna segment is not located on the neutral axis for bending of the supporting beam, the bending motion of the beam generates stretching of the antenna segment. Calculations indicate that the antenna output due to the induced stretching is comparable to the

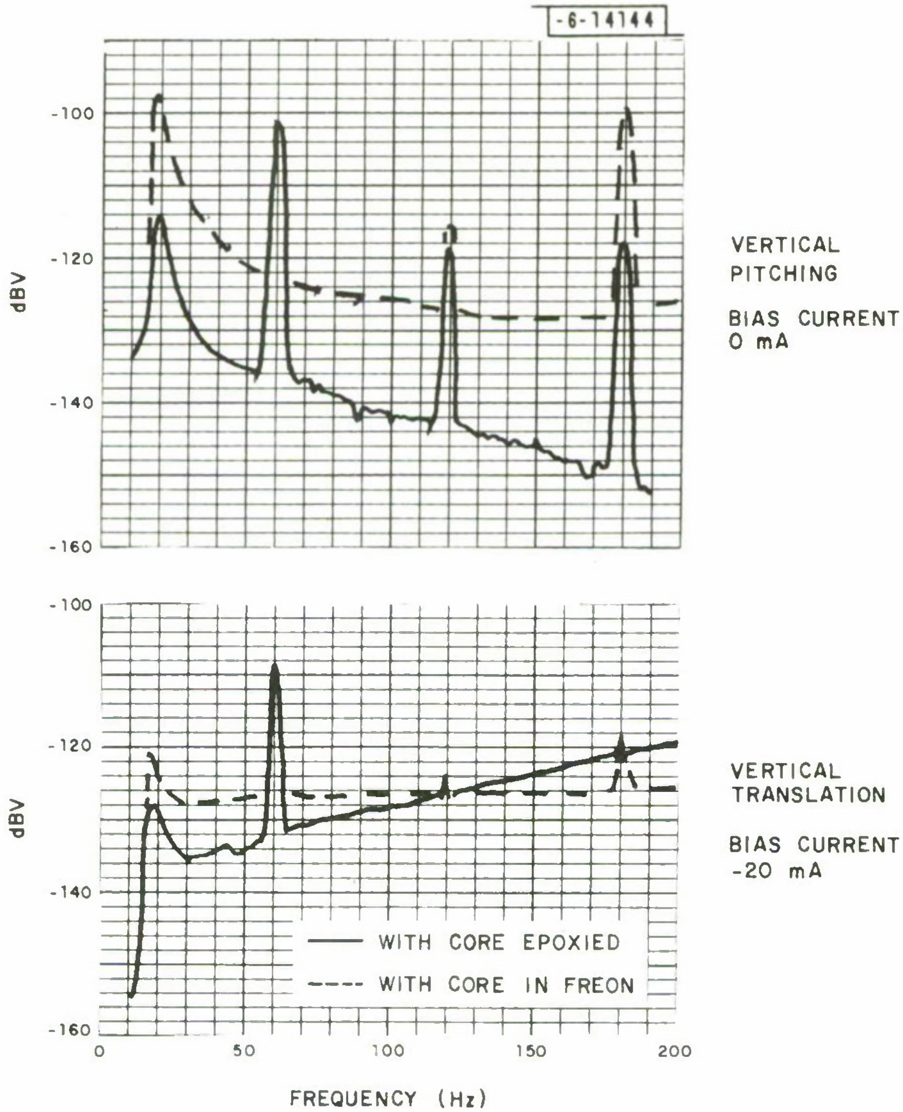


Fig. 17. Comparison of antenna output with core epoxied and core in Freon.

measured output. In later experiments, Burrows connected the antenna segment on the side of the supporting beam (at the neutral axis) and observed a large decrease in antenna output due to vertical translation. Based on this result, it appears that epoxying the core eliminates the vertical translation induced antenna output.

As a final experiment the antenna segment with epoxied core was subjected to stretching vibration at 45 Hz. The linearity of the output with respect to the shaker input level is shown in Fig. 18. At low levels of vibration the output for the case with epoxied core is approximately equal to the output for the case with the core in Freon. At higher levels the output for the case with epoxied core continues to be linear. The output for the case with the core in Freon becomes highly nonlinear.

Although the results can be questioned because the core has different properties in the two cases, they clearly support the idea advanced in section 5 that above a certain level the core in Freon is isolated from the bifurcated tube while below that level the core sticks to the tube and is not isolated.

7. Conclusions

As a result of the vibration experiments, the author has come to a number of reasonable, though tentative, conclusions. These are:

1) The noise output during the sea trials was a result of stretching the antenna cable. Data on towed cable vibration is needed to support this conclusion.

2) At low levels of vibration the core bundles are not isolated from the tube vibration and longitudinal strain.

3) Some reduction in noise could be achieved in sea tests by isolating the antenna section from the rest of the cable. Again data on cable vibration is needed to support this conclusion.

4) To achieve the goal of a 50 dB reduction in vibration-induced noise a new cross-sectional design will have to be used. In this design the core will have to be dynamically isolated from all cable strain.

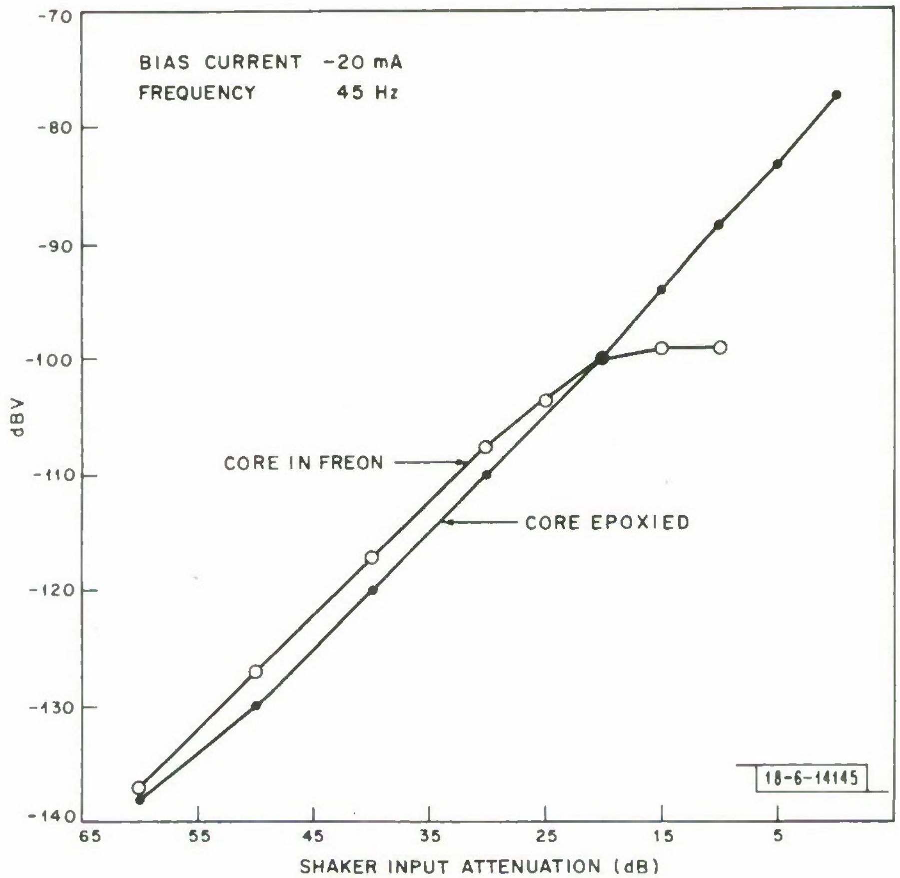


Fig. 18. Antenna output linearity during stretching vibration — core epoxied and core in Freon.

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DOCUMENT CONTROL DATA – R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Lincoln Laboratory, M.I.T.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP None
3. REPORT TITLE Vibration and Strain-Induced Noise from the ELF Flexible Loop Antenna	
4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)* Technical Note	
5. AUTHOR(S) *(Last name, first name, initial)* Manning, Jerome E.	

6. REPORT DATE 15 December 1971	7a. TOTAL NO. OF PAGES 38	7b. NO. OF REFS 2

8a. CONTRACT OR GRANT NO. F19628-70-C-0230 b. PROJECT NO. 1508A c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Note 1971-51 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* ESD-TR-71-321
10. AVAILABILITY/LIMITATION NOTICES Approved for public release; distribution unlimited.	
11. SUPPLEMENTARY NOTES None	12. SPONSORING MILITARY ACTIVITY Department of the Navy

13. ABSTRACT

Measurements have been made on a segment of the ELF flexible loop antenna to study its electrical sensitivity to vibration and strain. Transfer functions for the output voltage resulting from various types of vibration and strain were determined as functions of frequency, bias current, and orientation with respect to the gravitational field. Based on these laboratory measurements, it is tentatively concluded that the principle source of noise for the flexible loop antenna towed from a submarine is longitudinal strain.

14. KEY WORDS

ELF	gravitational field	communications
flexible loop antenna	longitudinal strain	vibration
electrical sensitivity		